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Review and Experimental Investigation of Phase Change Material Use in Buildings

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REVIEW AND EXPERIMENTAL INVESTIGATION OF PHASE CHANGE MATERIAL USE IN BUILDINGS

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Abstract:

This paper presents an overview of phase change materials (PCM) and their properties along with a review of relevant studies conducted in the past several years over phase change materials. An experiment is conducted to examine the differences between external building walls with and without bio-based phase change materials. In addition, the length of time BioPCM requires to completely change phase is examined from the data. Based on the data, the internal wall temperature of a home can be reduced by approximately 2 F. Additionally, a theoretical case study is presented and it is concluded that with the use of phase change materials energy savings of approximately 58% are possible in warm climates under several assumptions about how the PCM handles heat.

Contents

Chapter 1: Introduction

With the growing global need for energy, we cannot rely solely on renewable energy sources and efficient generation of power to solve our problem; instead, we must attack from both an energy production and energy conservation angle. Once we have produced the energy, how can be use it to its maximum potential?

There are many practical avenues to pursue in the realm of energy conservation. To further subdivide this discussion, we will discuss in particular, the use of phase change materials in the effort to conserve energy on multiple fronts; particularly within buildings.

Phase change materials, or PCM's, are a form of latent heat of storage (LHS) devices. These materials utilize the natural phenomenon of latent heat to influence their individual surroundings. When a material changes state from solid to liquid, liquid to gas, or vice versa on the chemical level there is a release or absorption of energy associated with the breaking or forming of chemical bonds. When this happens, any thermal energy added to the system is used to change the phase of the material and the temperature does not change.

An excellent example of phase change is with an ordinary glass of water. For this example, imagine the water is at room temperature and is then left outside on a cold day in Calgary Canada at a frigid -20 F. The temperature will decrease until it reaches 32 F when the water begins to freeze, as the water freezes, the temperature does not change, but as time passes a larger amount of water freezes with respect to the total volume. Once the entire volume of water is frozen, the temperature of the water, now ice, continues to drop. If this same, now frozen, glass was removed from the frigid outdoors and placed back into an ambient temperature of 72 F, the reverse would occur: the ice would change phase back into water.

The important take-away from this example is time. For a certain period of time, the glass of water remained 32 F even though the surroundings were significantly cooler. How long this change occurs is dependent on many factors including (but not limited to): material, temperature, and volume.

Imagine there is a sensitive product that must be shipped at exactly 32 F; surrounding this product with a mixture of ice and water would be an excellent solution temporarily. What if however the product under consideration required a more specific temperature, say 42 F? Or, with a home, say you wanted to keep the temperature of the room to as close to room temperature as possible, say 72F, ice would not be an appropriate solutions.

These questions are the basis for the study of Phase Change Materials. How can we effectively maintain the temperature of an object or space without the use of heating and cooling equipment requiring energy of their own?

NASA set out to discover a solution to this problem in the early 1980's to provide "thermal protection against the extreme thermal fluctuations of outer space" [4]. This initial research has sparked interest for a diverse array of applications.

There are many unique applications of PCM's. Several are listed below [11]:

1) Textiles
   a) Athletic apparel
   b) Work apparel
2) Construction
   a) Insulation or walls and roofs
   b) Cooling of walls and roofs
3) Medical
   a) Treatment for patients with hypothermia
   b) Drug transportation
   c) Organ transportation
4) Consumer Products
   a) Thermos
   b) Food transportation
   c) Vehicle comfort
   d) Engine cooling
   e) Mattresses
5) Food Production
   a) Wine
   b) Milk
6) Aeronautics
   a) Spacecraft
   b) Astronaut apparel and equipment

The focus of this review will be on thermal energy storage and phase change materials in the realm of construction. Specifically, how PCM's are used in walls of buildings.

Phase Change Materials can be classified into three, broad categories: organic, inorganic, and eutectic (Figure 1). A complete list of advantages of disadvantages can be found in Appendix A, Figure 11.

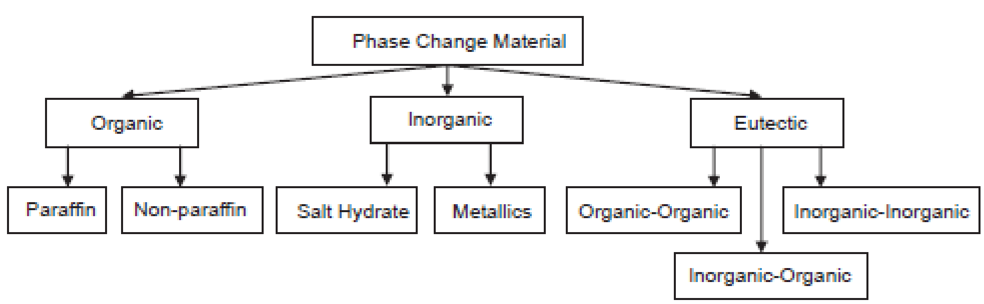

Figure 1: Classifications of Phase Change Materials (11)

There is no universally accepted collection of desirable qualities for a given application. For example, within the construction industry every building is different creating a need for a different balance between cost, chemical properties, physical properties, and environmental properties [11].

A full list of materials can be found in Zalba's *Review on Thermal Energy Storage* [18].

In the construction industry, there are several primary means of incorporating PCM:

1. Direct Incorporation
2. Immersion
3. Encapsulation
4. Microencapsulation
5. Macroencapsulation

Direct Incorporation is simply mixing PCM with the material used for construction. Direct incorporation is cost effective; however, considerations must be made to prevent the compromise of positive qualities within the material being mixed with the PCM such as durability or bonding [11]. In addition, direct incorporation can lead to leakage within the system [11].

Immersion is the process of submerging manufactured construction elements in PCM. The PCM is absorbed into the material giving the body desirable thermal properties. It should be mentioned that after numerous cycles the PCM may leak and the construction elements may lose their thermal properties [11].

Encapsulation is the process of containing a portion of PCM within a barrier that prevents leakage while providing strength and stability to the material [11]. Limiting factors to encapsulation are dependent on the application; however, surface area and heat transfer efficiency are the primary factors.

Encapsulation is broken down into Micro and Macro encapsulation techniques. Microencapsulation is any PCM in between 1 and 1000 microns [11]. Macroencapsulation is any significant portion of PCM within a container.

Objective

The objective of this study was to show the effectiveness of bio-based PCM for building applications, specifically in external walls. Background research was overviewed and an experiment was discussed. This experiment helped to quantify the temperature and heat flux differences between walls with and without PCM. A theoretical case study was addressed to assign economic vales to the experimental findings. In addition, this experiment tested the heat flux capacity of an M27 Bio PCM blanket.

Chapter 2: Background

Substantial research has been conducted on phase change materials over the past 40 years. Several citations have been made for several of the more recent studies that have been completed. These studies have been broken down into three categories: general reviews of phase change materials, physical experimentation on phase change materials, and simulated experiments on phase change materials.

Reviews

In 2013, Memon published a state of the art review on phase change materials, specifically for uses within building walls. An extensive overview of the many incorporation styles is discussed. Analysis techniques used to determine PCM thermal properties, chemical compatibility, and thermal stability are reviewed. Possibilities for means of increasing desirable thermal properties are proposed. Applications and suggestions for further research are revealed [11].

Li published an overview of the use of phase change materials to improve energy efficiency in 2014. This report gives a history of PCM development, an overview of PCM classifications and desirable properties, and finally applications PCM materials would be appropriate for. Opportunities for future research are discussed [9].

Madessa delivered an overview of PCM specifically in cold climates to reduce energy demand and improve thermal comfort. This review gives an excellent overview of the different studies performed based on building element (ceiling, floor, wall, window, etc.), PCM type, Integration technique, and relevant findings based on research [10].

Konuklu delivered a comprehensive report on the encapsulation techniques used in several application of PCM. In addition, the study gives an overview of the tests that have been performed on PCM to rate its performance in building applications. The report concluded that PCM will increase the thermal capacity of buildings if applied correctly with the proper encapsulation techniques without any significant drawbacks [7].

Cui published an overview of phase change materials specifically for building walls for energy savings. Selection criteria are discussed, PCM variations are listed, implementation techniques are compared, and applications are reviewed. In addition, optimization of PCM with respect to its position is mentioned in more detail along with the use of PCM in union with solar concentrators [2].

Farid's review on phase change materials focused primarily on application techniques in building applications as well as a thorough overview of the classifications and properties of phase change materials [3].

Physical Experimentation

In 2010, Ceron studied the use of PCM tile for buildings. In this study, two tiles (one with PCM and one without) were placed side by side and their temperatures were tracked over time. It was unveiled that while PCM tiles were viable options, they were only effective when exposed to direct sunlight throughout the day and they were only effective for passive heating applications [1].

Kenisarin studied PCM application for passive thermal control in buildings in 2014. The test consisted of 15 full sized buildings. It was concluded that paraffins, fatty acids and their mixtures are viable phase change materials for building applications [5]. Using PCM in gypsum wallboards with percentages ranging from 25 to 30 by weight will increase the wallboard's thermal capacity by a factor of 10 without any noticeable negative effects [5]. In addition to these findings, further research is encouraged in the areas of accurate mathematical models for PCM incorporating climate and annual temperature variations, construction element design centered on the incorporation of PCM, narrowing of temperature ranges within PCMs, and large scale cost reduction for encapsulated PCM materials [5].

Kuznik studied two identical office spaces, one was renovated with PCM and the other was not. The renovation consisted of installing PCM material into the walls and the ceiling [8]. The study was conducted over one calendar year. It was concluded that both wall and air temperature in the PCM renovated room was more comfortable than the room without PCM. This is the case only if the phase change temperature of the PCM is near the range of temperatures within the room itself and the inertia of the building is low [8].

Solgi studied the use of night purge combined with PCM in an arid climate to reduce the cooling load of a building. Night purge, in essence, is a cooling method used in dry climates to reduce HVAC load by ventilating cool air from the outside during night hours [16]. Night purge fans were set to only allow 30 C air into the office buildings, the melting point selected for the PCM was 27 C, and ventilation rate was optimized to 15 ach [16]. This combination provided a 47% reduction in energy for the HVAC system [16]. PCM was used on all elements of the building, walls, ceilings, and floors, all elements decreased the cooling load with the exception of the floor which prevented hot air from escaping to the soil below [15]. It was concluded that the priority for installation was as follows: “south, west, and east walls, ceiling and north wall respectively” [16].

Shilei conducted several experiments utilizing differential scanning calorimetry to evaluate PCM used in wallboards for building applications [15]. It was concluded the impregnated PCM within gypsum wallboards provided enough cooling load support to shift the peak cooling load to off-peak hours [15]. In addition, it was proven that DSC could be used to predict large scale PCM applications [15].

Simulated Experimentation

Ozenefe conducted experiments on residential buildings in Cyprus to gauge thermal performance of PCM using simulation [14]. In all scenarios, cooling load was reduced with the application of PCM material, especially in homes with low heat capacity and relatively quick thermal responses to shortwave radiation [14]. Night purge ventilation is recommended to further decrease cooling load during daytime hours in combination with PCM [14].

Sun studied the economic and energy conservation benefits of using PCM board in Chinese buildings using simple payback period and energy savings ratio [17]. Since HVAC systems are specified for the peak hours of the most temperature extreme days of the year, these systems tend to run at lower efficiencies and loads for the majority of the year, costing money and wasting energy [17]. PCM combined with night purge is the proposed solution to this problem to offset peak loads, decrease the energy required to satisfy comfort demands, and ultimately decrease the size and requirements of HVAC systems [17]. It was concluded that in order for PCM to economically viable, the phase change temperature must be 3 C above the average outdoor air temperature [17].

Muruganantham investigated energy efficiency improvement using bio-based PCM. The study was completed in cooperation with Arizona Public Service and Phase Change Energy Solutions Inc. It was discovered that bio-based PCM significantly decreases cost (30%) while increasing efficiency in the summer months [13]. Furthermore, it the peak load of the building was shifted (60 mins) to off-peak hours of the grid, increasing savings [13].

Chapter 3: Methodology

A device will be made to simulate an external wall of a home. The device will contain M27 BioPCM, insulation, and gypsum board. The device will be exposed to heat from a brooder lamp to simulate the rays of the sun. Temperatures will be recorded at different points on the device throughout the experiments.

A cut-away of the device is shown below in Figure 2. The rendering of the device was made using SolidWorks.

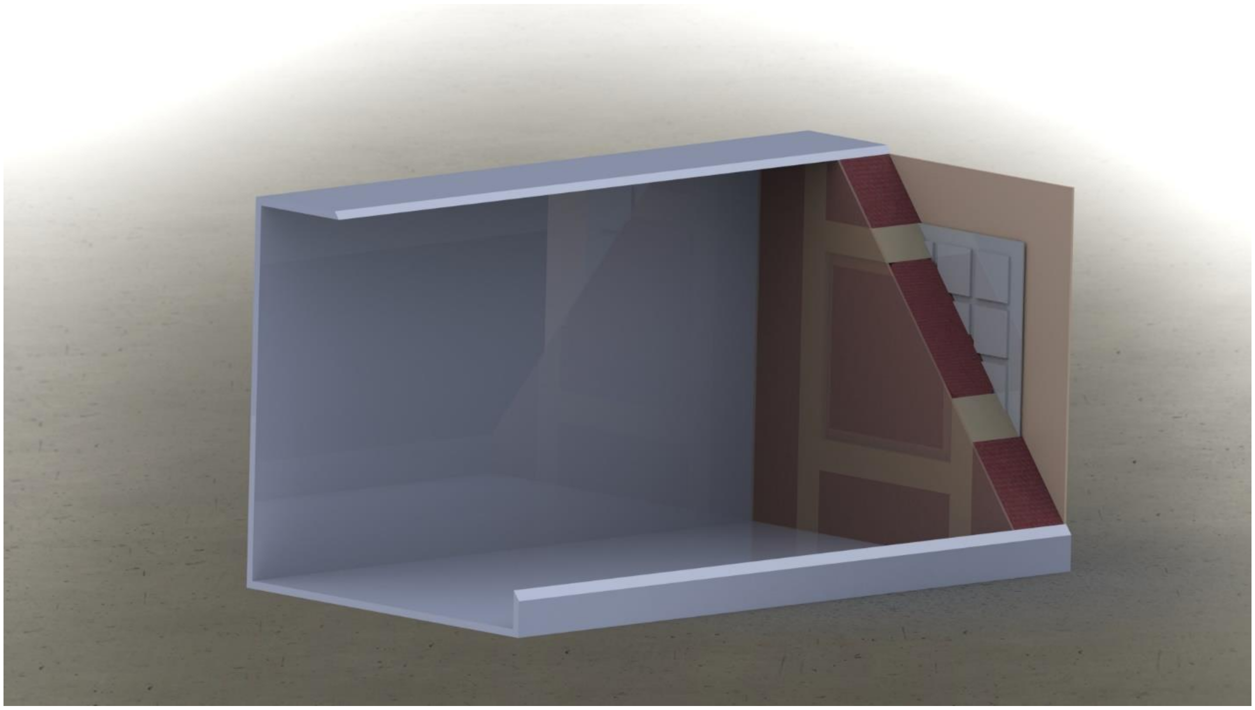

Figure 2: Device

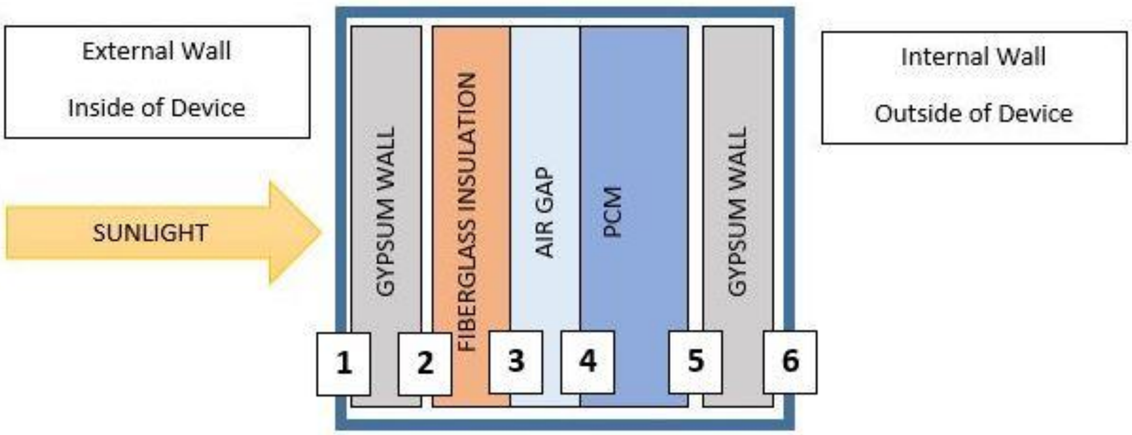

Figure 3: 2D Diagram of Wall

The device was designed to create a warm environment with direct sunlight facing one of the gypsum walls. The inside of the device simulated the external wall of a home while the outside of the device simulated the internal wall of a home. This is the nomenclature when referencing portions of the device.

In addition, the portion under analysis was the wall. This portion has several layers:

- Gypsum board (external)
- Insulation (if applicable)
- PCM
- Gypsum board (internal)

The layers were arranged in accordance with the BioPCM website with the PCM placed closest to the internal (or “outside”) wall [19]. A diagram of the wall is shown in Figure 3.

The experiment consisted of several phases:

- With PCM
- Without PCM (control)
- With PCM, without center insulation layer
- Without PCM, without center insulation layer (control)

The purpose of removing the insulation layer in the center was to speed up the process of melting the PCM material.

Materials

Below are the materials that were used in this experiment:

- 60 W Grow Bulb, Figure 12
- 125 W Heat Lamp
- Brooder Lamp with Hang Hook, Figure 12
- 2x4’’ Stud, 96 in., Figure 13
- MP r6.7 unfaced fiberglass Figure 14
- 2 in. 30 ft reflective tape, Figure 15
- 2x2’ 0.5 in. gypsum sheetrock; Figure 17
- 4x8’ ¾ in. Aluminum faced Styrofoam; Figure 18
- Bio PCM Phase Change Material; Figure 19
- Power Screwdriver
- Wood Screws
- Infrared Camera, Figure 34
- Temperature Humidity meter, Figure 31
- Pyrometer, Figure 27
- Thermal Couple, Figure 33
- Data logger, Figure 32
- Trash bag, Figure 26
- Microsoft Excel
- Solidworks

Procedure

The following steps were performed between April 21, 2016 and April 26, 2016

Assembly

The following steps were performed on April 21, 2016

1. Obtained required materials
2. Constructed wooden frame, Figure 20
3. Fastened wooden frame to single piece of gypsum board, Figure 20
4. Filled center with insulation, Figure 21
5. Fastened PCM to wooden frame, Figure 22
6. Fastened second piece of gypsum board to wooden frame parallel to other piece
7. Filled outside spaced between the frame and perimeter of board with insulation, Figure 21
8. Fastend ends of foam board to gypsum board so that the aluminum side is facing towards each other, Figures 24 and 25.
9. Used aluminum tape, attached the foam board to one another so that there are no spaces. The tape was placed on the aluminum side of the foam board, Figures 24 and 25.
10. Used aluminum tape, sealed the spaced between the gypsum board and the foam board on the interior of the device.
11. Stapled the trash bag to the end of the device, Figure 26.
12. Assembled the lamp with the 60 watt bulb, Figure 12.
13. Placed the lamp inside the device with the bulb shining perpendicular to the internal gypsum wallboard. Prop the lamp on something to ensure this is so, Figure 28.
14. Bored a hole in the top of the device through the foam board directly above the lamp so that the tip of the thermometer (or other temperature reading device) can be inserted, Figure 27.

Experimentation

Calibration:

The following steps were performed on April 21, 2016

1. Recorded internal temperature
2. Turned on lamp
3. Secured trash bag so that there are no spaces for heat to escape.
4. Every 30 minutes checked the internal temperature
5. Recorded the steady state temperature of the device
6. Turned off lamp
7. Gave device at least 12 hours to allow the PCM to return to solid phase

Phase 1: Test with PCM and 60 watt grow lamp

The following steps were performed on April 22, 2016

1. Recorded thermal image of both gypsum wallboards.
2. Recorded internal and external temperature
3. Turned on lamp
4. Secured trash bag so that there are no spaces for heat to escape.
5. Repeated steps 1 and 2 every 30 minutes for 8 to 12 hours.

    a. The time interval can be increased to every hour after 4 hours
6. After 8 to 12 hours, turned off the lamp and remove the trash bag to allow the device to return to room temperature.

Phase 2: Test with PCM and 125 watt grow lamp

The following steps were performed on April 23, 2016

1. Recorded thermal image of both gypsum wallboards.
2. Recorded internal and external temperature
3. Replaced the 60 watt bulb with a 125 watt bulb and turn on lamp
4. Secured trash bag so that there are no spaces for heat to escape.
5. Repeated steps 1 and 2 every 30 minutes for 8 to 12 hours.
    a. The time interval can be increased to every hour after 4 hours
6. After 8 to 12 hours, turned off the lamp and remove the trash bag to allow the device to return to room temperature.

Phase 3: Test without PCM and 125 watt grow lamp

The following steps were performed on April 24, 2016

1. Recorded thermal image of both gypsum wallboards.
2. Recorded internal and external temperature
3. Turned on lamp
4. Secured trash bag so that there are no spaces for heat to escape.
5. Repeated steps 1 and 2 every 30 minutes for 8 to 12 hours.
    a. The time interval can be increased to every hour after 4 hours
6. After 8 to 12 hours, turned off the lamp and remove the trash bag to allow the device to return to room temperature.

Phase 4: Test with PCM and 125 watt grow lamp without center piece of insulation

The following steps were performed on April 25, 2016

1. Using tape, attached end of thermocouple to the center of the external piece of gypsum board.
2. Recorded data with the data logger.
3. Recorded thermal image of both gypsum wallboards.
4. Recorded internal and external temperature
5. Turned on lamp
6. Secured trash bag so that there are no spaces for heat to escape.
7. Repeated steps 1 and 2 every 30 minutes for 8 to 12 hours.
    a. The time interval can be increased to every hour after 4 hours
8. After 8 to 12 hours, turned off the lamp and remove the trash bag to allow the device to return to room temperature.

Phase 5: Test without PCM and 125 watt grow lamp without center piece of insulation

The following steps were performed on April 25, 2016

1. Using tape, attached end of thermocouple to the center of the external piece of gypsum board.
2. Recorded data with the data logger.
3. Recorded thermal image of both gypsum wallboards.
4. Recorded internal and external temperature
5. Turned on lamp
6. Secured trash bag so that there are no spaces for heat to escape.
7. Repeated steps 1 and 2 every 30 minutes for 8 to 12 hours.
    a. The time interval can be increased to every hour after 4 hours
8. After 8 to 12 hours, turned off the lamp and remove the trash bag to allow the device to return to room temperature.

Notes:

1. Phase 1 is not necessary to complete the experiment, the 60 watt bulb was used originally because it was thought to be sufficient. The temperature with the device was insufficient so a more powerful bulb was selected.
2. The pyrometer was exchanged for the temperature and humidity monitor between phases 1 and 2 due to an electronic failure. The pyrometer was removed and a larger bore was made in the foam to accommodate the temperature and humidity monitor.

Data

Thermal data was taken for all five phases. Each phase consisted of slightly different measurement techniques. The techniques used in each phase are outlined below:

1. Phase 1: (Note: data from phase 1 was discarded due to the insufficient light bulb strength)
    a. Thermal images
    b. Pyrometer readings
    c. Thermostat readings
2. Phase 2:
    a. Thermal images
    b. Pyrometer readings
    c. Thermostat readings
3. Phase 3:
    a. Thermal images
    b. Thermostat readings
    c. Temperature Humidity meter readings
4. Phase 4:
    a. Thermal images
    b. Thermostat readings
    c. Temperature Humidity meter readings
    d. Data logger with thermocouple
5. Phase 4:
    a. Thermal images
    b. Thermostat readings

c. Temperature Humidity meter readings
d. Data logger with thermocouple

Thermal images were taken of the inside and outside pieces of gypsum board. The images were taken approximately perpendicular to the boards with the images encompassing the entire piece. Two example images are shown below in Figure 4. The image on the right is of the outside piece of gypsum board exposed to the air conditioned room. The image on the left is of the inside piece of gypsum board enclosed within the device with the lamp shining on it.

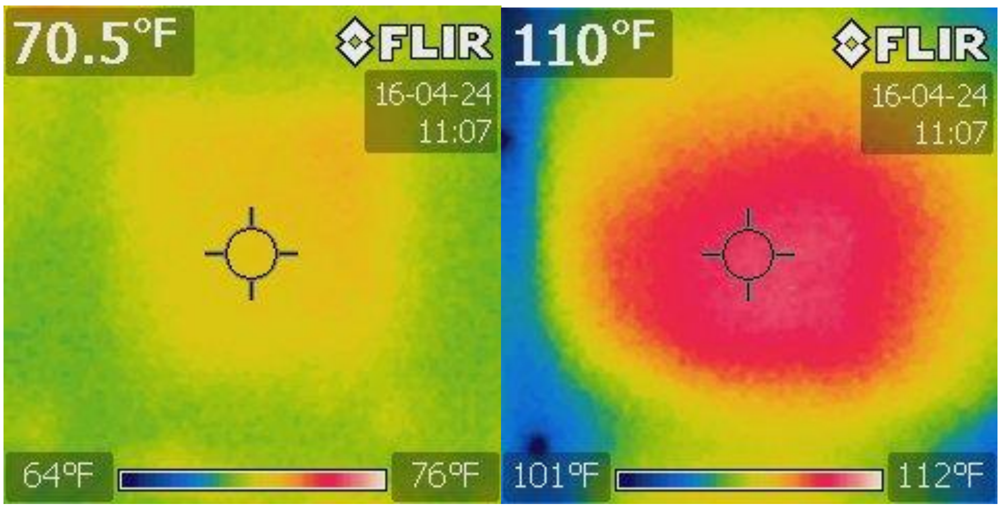

Figure 4: Example Thermal Images

Each photo provides several pieces of information: a timestamp (upper right), the approximate temperature in the center of the image (upper left), and the range of temperatures in the image represented by a “rainbow” color scale (bottom).

Representative thermal images are available in Appendix E. All thermal images can be made available upon request of the author.

Data collected for each phase of the experiment is available in Appendix B.

A sample of the data taken by the data loggers is located in Appendix D, all data logger raw data is available upon request of the author.

Analysis

Data was compiled and analyzed using Microsoft Excel.

The thermal conductivity (k) was calculated for each of the following materials: gypsum and fiberglass insulation. The heat transfer coefficient (h) was calculated for air. These values were found using Engineering Toolbox [20] and the packaging from the insulation.

Table 1: Material Properties

Description	Notation	Amount	Units
Thermal conductivity - gypsum	k-gy	1.1798	Btu in. / hr ft^2 F
Thermal conductivity - insulation	k-ins	0.298507	Btu in. / hr ft^2 F
Heat Transfer Coefficent - air	h-air	3.16998	Btu/hr ft^2

In addition, several properties of the device were measured in order to perform the analytical calculations needed. These measurements are shown below in Table 2:

Table 2: Device Measurements

Description	Notation	Amount	Units
Area -PCM Area	A-pcm	1.777778	ft^2
Thickness - Gypsum	L-gy	0.5	in.
Thickness - Insulation	L-ins	2	in.

Using the Thermal Resistance Method for one dimensional systems the overall heat transfer coefficient (U) for each component of the device was calculated with and without insulation as shown below in Table 3. In addition, the overall heat transfer coefficient was calculated for the section in front of the PCM (1 to 4, referencing Figure 3). It should be noted that the thermal resistance of the PCM was assumed to be negligible.

Table 3: Thermal Resistance Calculations

PCM Area			
Description	Notation	Amount	Units
Thermal Resistance- gypsum 1	R-1	0.238	(hr F)/ Btu
Thermal Resistance- insulation	R-2	3.769	(hr F)/ Btu
Thermal Resistance- air	Rc-1	0.177	(hr F)/ Btu
Thermal Resistance Total (no insulation)	R-tot-ni	0.654	(hr F)/ Btu
Thermal Resistance Total (pre pcm)	R-tot-prp	4.185	(hr F)/ Btu
Thermal Resistance Total (pre pcm no ins)	R-tot-prpr	0.416	(hr F)/ Btu
Thermal Resistance Total	R-tot	4.423	(hr F)/ Btu
Overall Heat Transfer Coef (No Ins)	U-ni	0.860	Btu/(hr ft^2 F)
Overall Heat Transfer Coef (pre pcm)	U-prp	0.134	Btu/(hr ft^2 F)
Overall Heat Transfer Coef (pre pcm no ins)	U-prpni	1.353	Btu/(hr ft^2 F)
Overall Heat Transfer Coef	U	0.127	Btu/(hr ft^2 F)

Using the overall heat transfer coefficients and the data measured by the infrared camera, the heat flux through the entire wall area was calculated with and without insulation (Table 4 and 5).

Since the points on the inside board of gypsum were measured at the hottest point, the temperatures are adjusted to be more realistic by reducing the temperatures be 3 F (Tables 18 and 19). This number was selected based on the thermal images similar to Figure 4 (right side). The temperatures were averaged over the diameter of the area containing the PCM.

Though the PCM is theoretically undergoing a phase change, the thermal resistance equations are used to determine the inside temperature of the PCM layer (point 4 on Figure 3) since the temperatures were not directly measured (Table 4 and 5).

To simplify the calculation, it is being assumed that the PCM is not losing heat to the air conditioned room and only gaining heat from the lamp (Tables 6 and 7).

Using the heat flux and the time interval over which the experiment was run, the incremental energy storage was calculated by integrating the heat flux with respect to time using the trapezoidal rule for estimating integrals. These densities were summed to calculate the total cumulative energy storage into the PCM layer (Table 6 and 7).

Furthermore, the heat transfer through the wall (in Btu/hr) was integrated over time to determine the total BTUs transferred over the given period. These values were summed to determine the heat transfer over the entire experiment as shown in Tables 8 and 9.

Finally, using the same method as the configurations with the PCM, the total BTUs through the control configurations were also calculated as shown in Tables 10 and 11.

For an ideal situation, all heat through the device would be absorbed by the PCM until it reached its advertised energy capacity at 27 Btu/ft^2. This being said, an ideal, or adjusted, total BTUs was calculated using the same method mentioned above; however, the heat in Btu/hr into the PCM was subtracted from the total Btu/hr through the entire device for all points with a cumulative energy storage less than 27 Btu/ft^2 (Table 8 and 9). This adjusted calculation lowers the total BTUs through the systems containing PCM for a more ideal situation.

Motivation for this ideal, or adjusted, situation stemmed from the advertisement that the PCM would act like a 27 BTU air conditioner during the day [19].

Table 4: PCM with Insulation (1 to 6)

PCM with Insulation						
WALL (1 to 6)						
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	Delta T (°F)	q/A (Btu/hr ft^2)	q (Btu/hr)	PCM Inside Temp (°F)
0	67.8	67.8	0	0.00	0.00	67.80
0.46	91	69.3	18.7	2.38	4.23	70.31
1	107	68.2	35.8	4.55	8.09	70.13
1.55	110	69.1	37.9	4.82	8.57	71.14
2.15	111	69.6	38.4	4.88	8.68	71.67
3.35	114	69.3	41.7	5.30	9.43	71.55
4.3	114	69.3	41.7	5.30	9.43	71.55
5.11	112	69.6	39.4	5.01	8.91	71.72
6.45	105	70	32	4.07	7.23	71.72
7.45	113	70	40	5.09	9.04	72.16
9.61	113	69.4	40.6	5.16	9.18	71.59
10.85	112	69.8	39.2	4.99	8.86	71.91

Table 5: PCM Without Insulation (1 to 6)

PCM WITHOUT INSULATION						
WALL (1 to 6)						
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	Delta T (°F)	q/A (Btu/hr ft^2)	q (Btu/hr)	PCM Inside Temp (°F)
0	69	69	0.00	0.000	0.000	69.00
0.5	94.5	69.3	22.20	19.088	33.933	77.39
1.67	99	70.3	25.70	22.097	39.283	79.66
4	98.8	72.1	23.70	20.377	36.226	80.74
6.33	103	72.5	27.50	23.645	42.035	82.52
8.22	103	73.6	26.40	22.699	40.353	83.22
9.33	108	73.8	31.20	26.826	47.690	85.17
11.1	107	73.8	30.20	25.966	46.162	84.80

Table 6: PCM with Insulation (1 to 4)

PCM with Insulation						
PCM IN (1 to 4)						
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	q/A pcm (Btu/hr ft^2)	q pcm (Btu / hr)	Incremental Energy pcm (Btu / ft^2)	Cumulative Energy pcm (Btu / ft^2)
0.00	67.80	67.80	0.00	0.00	0.00	0.00
0.46	91.00	69.30	2.38	4.21	0.55	0.55
1.00	107.00	68.20	4.55	8.06	1.87	2.42
1.55	110.00	69.10	4.82	8.53	2.58	5.00
2.15	111.00	69.60	4.88	8.64	2.91	7.91
3.35	114.00	69.30	5.30	9.39	6.11	14.02
4.30	114.00	69.30	5.30	9.39	5.04	19.06
5.11	112.00	69.60	5.01	8.87	4.18	23.23
6.45	105.00	70.00	4.07	7.20	6.08	29.32
7.45	113.00	70.00	5.09	9.00	4.58	33.90
9.61	113.00	69.40	5.16	9.14	11.07	44.97
10.85	112.00	69.80	4.99	8.82	6.29	51.26

Table 7: PCM without Insulation (1 to 4)

PCM WITHOUT INSULATION						
PCM IN (1 to 4)						
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	q/A pcm (Btu/hr ft^2)	q pcm (Btu / hr)	Incremental Energy pcm (Btu / ft^2)	Cumulative Energy pcm (Btu / ft^2)
0.00	69.00	69.00	0.000	0.000	0.000	0.000
0.50	94.50	69.30	19.088	33.785	4.772	4.772
1.67	99.00	70.30	22.10	39.11	24.09	28.86
4.00	98.80	72.10	20.377	36.068	49.482	78.347
6.33	103.00	72.50	23.645	41.851	51.285	129.633
8.22	103.00	73.60	22.699	40.177	43.794	173.427
9.33	108.00	73.80	26.826	47.482	27.486	200.913
11.10	107.00	73.80	25.966	45.960	46.721	247.634

Table 8: PCM with Insulation BTU Calculations

PCM with Total BTUS								
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	q (Btu/hr)	q adj (Btu/hr)	Device Btus	Device Btus Adj	Total Device Btus	Total Device BTU adj
0	67.8	67.8	0.000	0.000	0.000	0.000	0.000	0.000
0.46	91	69.3	4.228	0.018	0.972	0.004	0.972	0.004
1	107	68.2	8.094	0.035	3.327	0.015	4.299	0.019
1.55	110	69.1	8.569	0.037	4.582	0.020	8.882	0.039
2.15	111	69.6	8.682	0.038	5.175	0.023	14.057	0.061
3.35	114	69.3	9.428	0.041	10.866	0.048	24.923	0.109
4.3	114	69.3	9.428	0.041	8.957	0.039	33.880	0.148
5.11	112	69.6	8.908	0.039	7.426	0.032	41.306	0.181
6.45	105	70	7.235	0.032	10.816	0.047	52.122	0.228
7.45	113	70	9.044	9.044	8.139	4.538	60.261	4.766
9.61	113	69.4	9.179	9.179	19.681	19.681	79.942	24.447
10.85	112	69.8	8.863	8.863	11.186	11.186	91.128	35.633

Table 9: PCM without Insulation BTU Calculations

PCM without Insulation Total BTUs								
Hours	Inside Wall Temp (°F)	Outside Wall Temp (°F)	q (Btu/hr)	q adj (Btu/hr)	Device Btus	Device Btus adj	Total Device Btus	Total Device Btus adj
0	69	69	0.00	0.00	0.00	0.00	0.00	0.00
0.5	94.5	69.3	33.93	0.15	8.48	0.04	8.48	0.04
1.67	99	70.3	39.28	0.17	42.83	0.19	51.32	0.22
4	98.8	72.1	36.23	36.23	87.97	42.40	139.28	42.63
6.33	103	72.5	42.03	42.03	91.17	91.17	230.46	133.80
8.22	103	73.6	40.35	40.35	77.86	77.86	308.31	211.66
9.33	108	73.8	47.69	47.69	48.86	48.86	357.18	260.52
11.1	107	73.8	46.16	46.16	83.06	83.06	440.24	343.58

Table 10: Control with Insulation Calculations

Control with Insulation							
Hours	Inside Wall Temp (ºF)	Outside Wall Temp (ºF)	Delta T (ºF)	q/A (Btu/hr ft^2)	q (Btu/hr)	Device Btus	Total Device Btus
0.00	70.20	70.00	0.20	0.03	0.05	2.52	2.52
0.64	104.00	69.30	34.70	4.41	7.85	10.23	12.76
1.87	110.00	71.10	38.90	4.95	8.79	8.59	21.35
2.87	108.00	70.90	37.10	4.72	8.39	16.52	37.87
4.67	115.00	70.90	44.10	5.61	9.97	21.65	59.52
7.02	109.00	71.60	37.40	4.76	8.46	17.78	77.31
9.09	110.00	71.40	38.60	4.91	8.73	7.81	85.12
9.99	110.00	71.80	38.20	4.86	8.64		85.12

Table 11: Control without Insulation Calculations

Control without Insulation							
Hours	Inside Wall Temp (ºF)	Outside Wall Temp (ºF)	Delta T (ºF)	q/A (Btu/hr ft^2)	q (Btu/hr)	Device Btus	Total Device Btus
0.00	72.10	70.70	1.40	1.20	2.14	48.49	48.49
2.08	105.00	75.90	29.10	25.02	44.48	41.27	89.76
3.08	101.00	76.10	24.90	21.41	38.06	37.91	127.66
4.08	101.00	76.30	24.70	21.24	37.75	62.34	190.00
5.67	104.00	77.40	26.60	22.87	40.66	43.25	233.25
6.75	103.00	77.20	25.80	22.18	39.44	80.30	313.56
8.65	107.00	77.50	29.50	25.36	45.09	58.35	371.90
9.98	106.00	78.10	27.90	23.99	42.65		371.90

Results

Based on the above analysis, several plotted results are available.

All four relevant phases are plotted below to show the device's outside wall temperature at different points during the experiment. Temperature is plotted on the y axis in degrees Fahrenheit and time is plotted on the x-axis in hours from the time the experiment started (Figure 5).

For phases 4 and 5 the data logger results are compared in Figure 6. As shown in Appendix B, there was between 0% and 3% between the values calculated by the Data Logger and the thermal images taken by the infrared camera.

In addition, the difference between the inside and outside wall of the device was calculated (ΔT). This difference is shown above in Figure 7 with the change in temperature on the y-axis and time in hours on the x-axis.

The cumulative energy storage for the phases involving PCM of the experiment were plotted (Figure 8). The line at the top of the graph represents the advertised energy storage capacity of the M27 PCM.

The cumulative energy storage for the PCM with the insulation surpassed 27 Btu/ft^2 approximately between 5.5 and 6.5 hours into the experiment. The cumulative energy storage for the PCM without insulation surpassed 27 Btu/ft^2 approximately between 1.0 and 1.67 hour into the experiment (Figure 8).

Finally, the BTUs through the device for the PCM and control configurations with insulation is graphed alongside the adjusted BTU calculation shown in Figure 9. The adjusted plot shows no heat through the system until the approximate time the PCM reaches its energy storage capacity where all additional heat is then allowed through the device and into the air conditioned room. This is assuming that the PCM absorbs all heat into the device prior to reaching this thermal capacity.

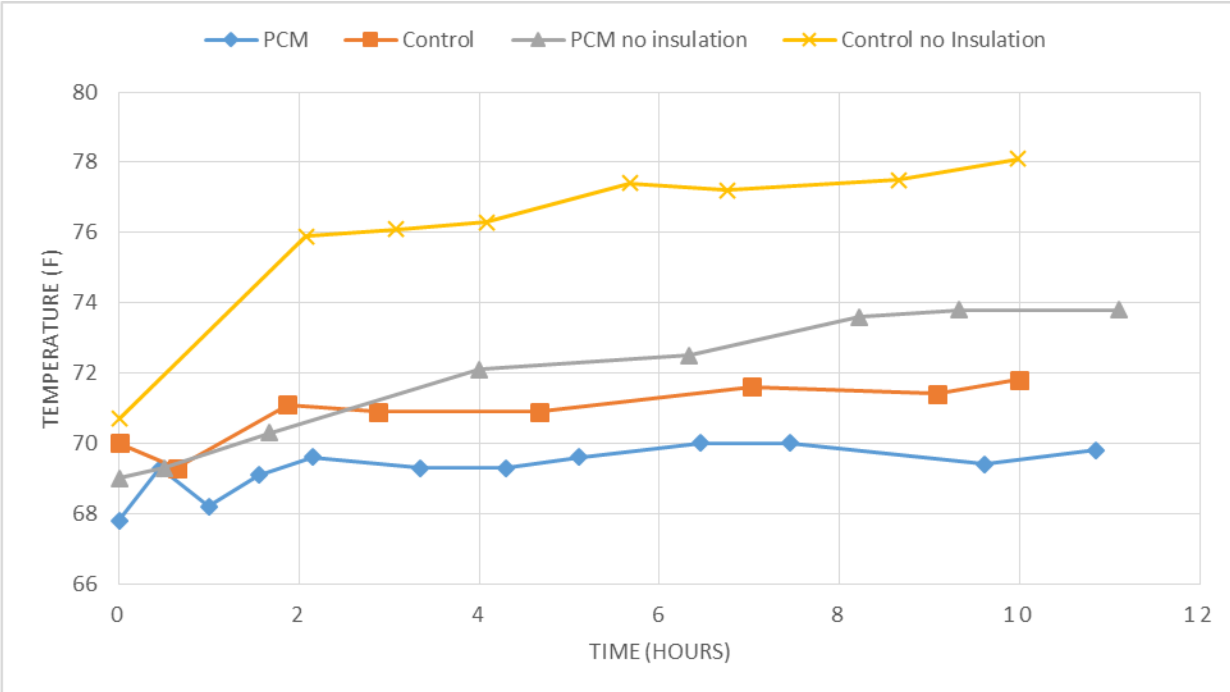

Figure 5: Outside Temperature v. Time

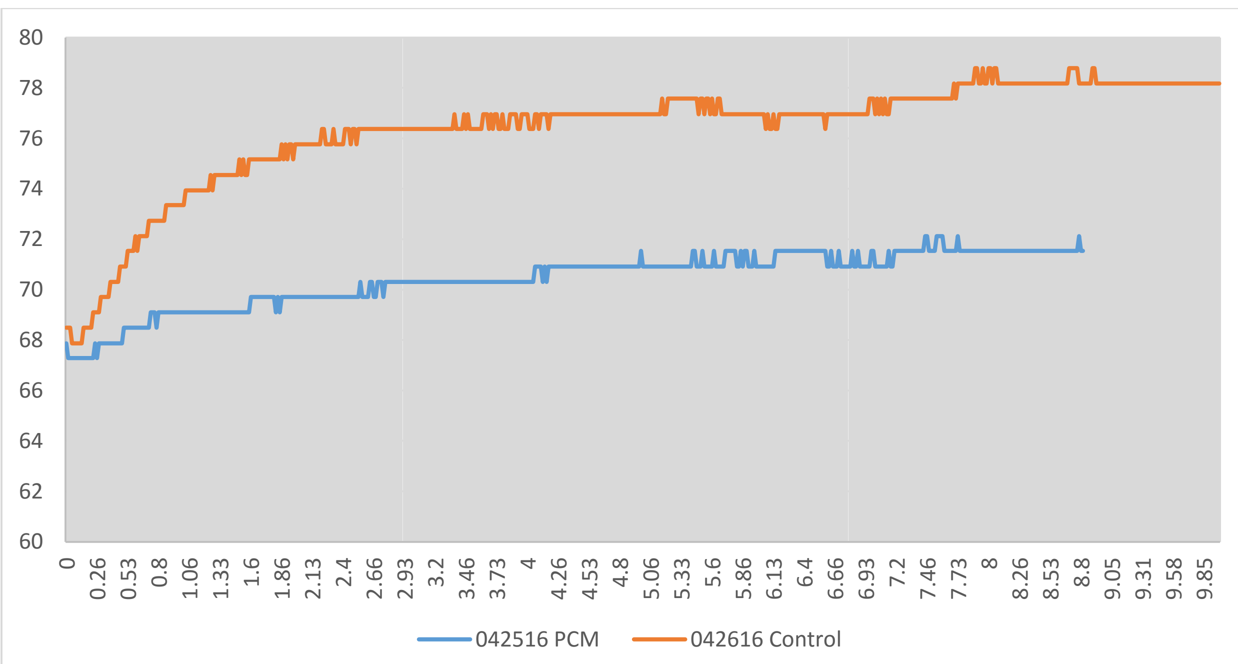

Figure 6: Data Logger Temperature Results

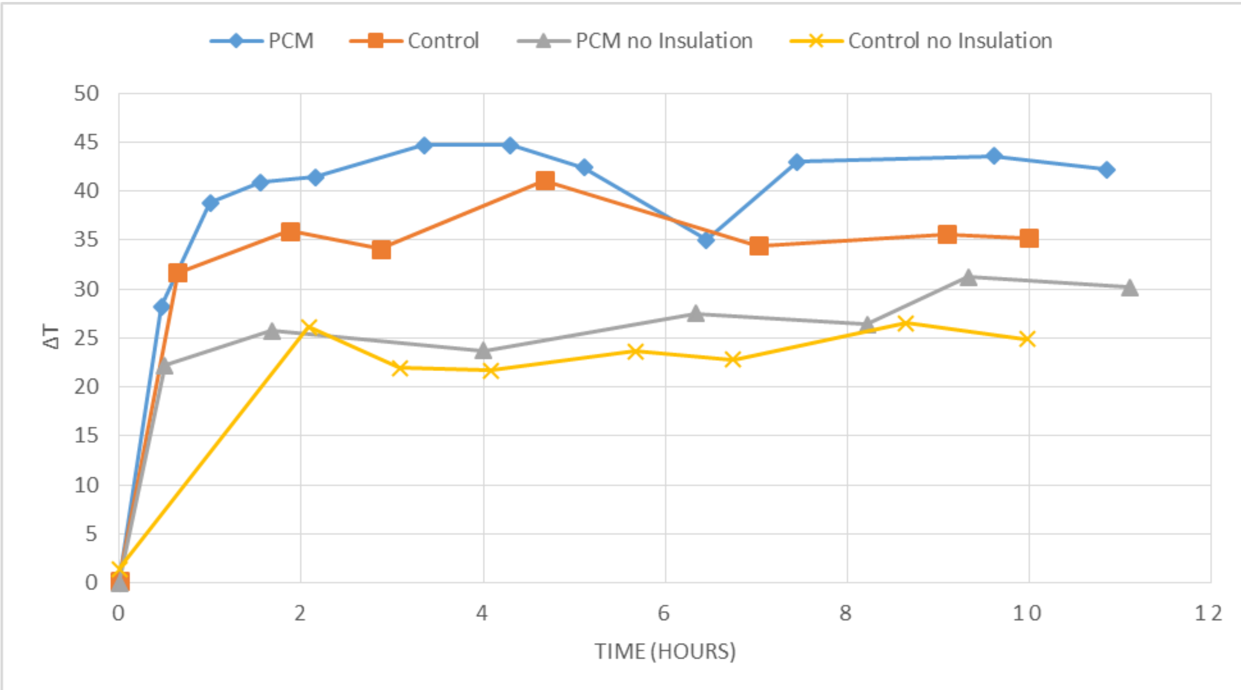

Figure 7: Difference in Temperature (Inside and Out) v. Time

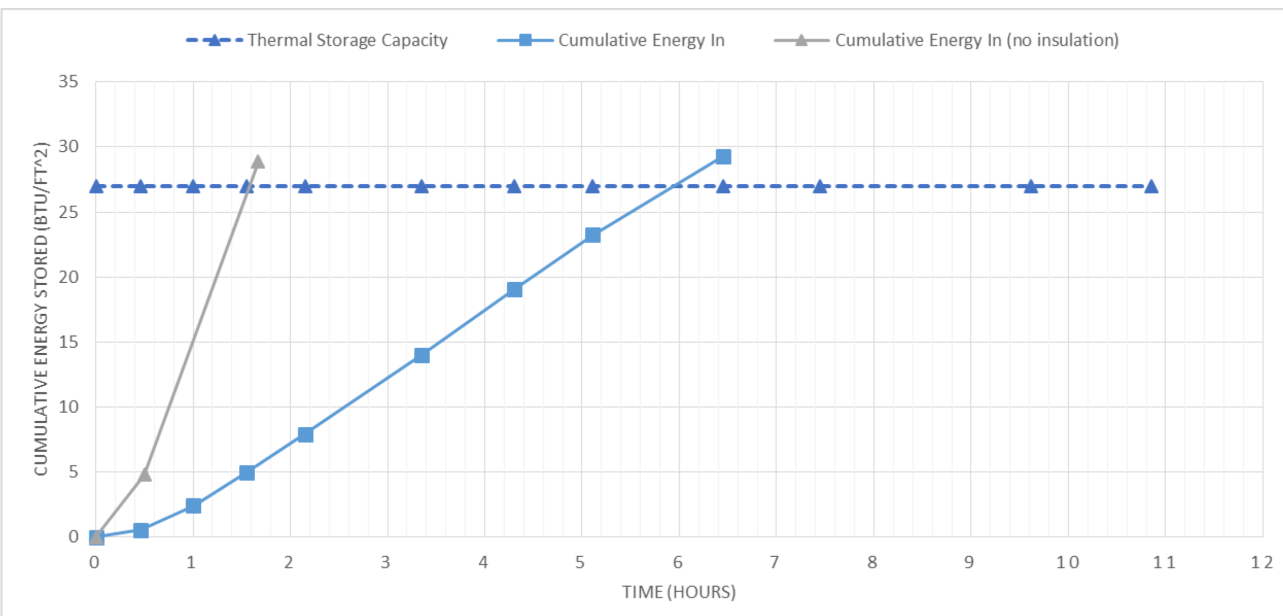

Figure 8: Cumulative Energy Stored v. Time

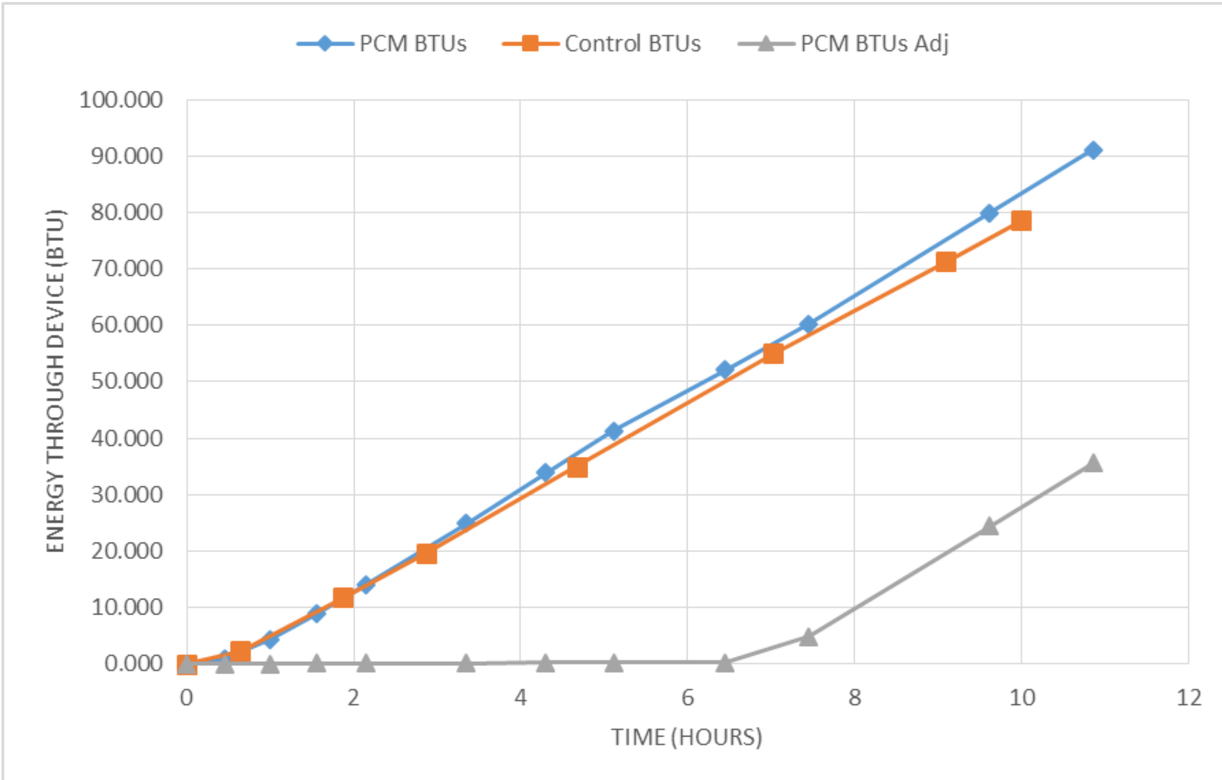

Figure 9: BTUs v. Time with Insulation

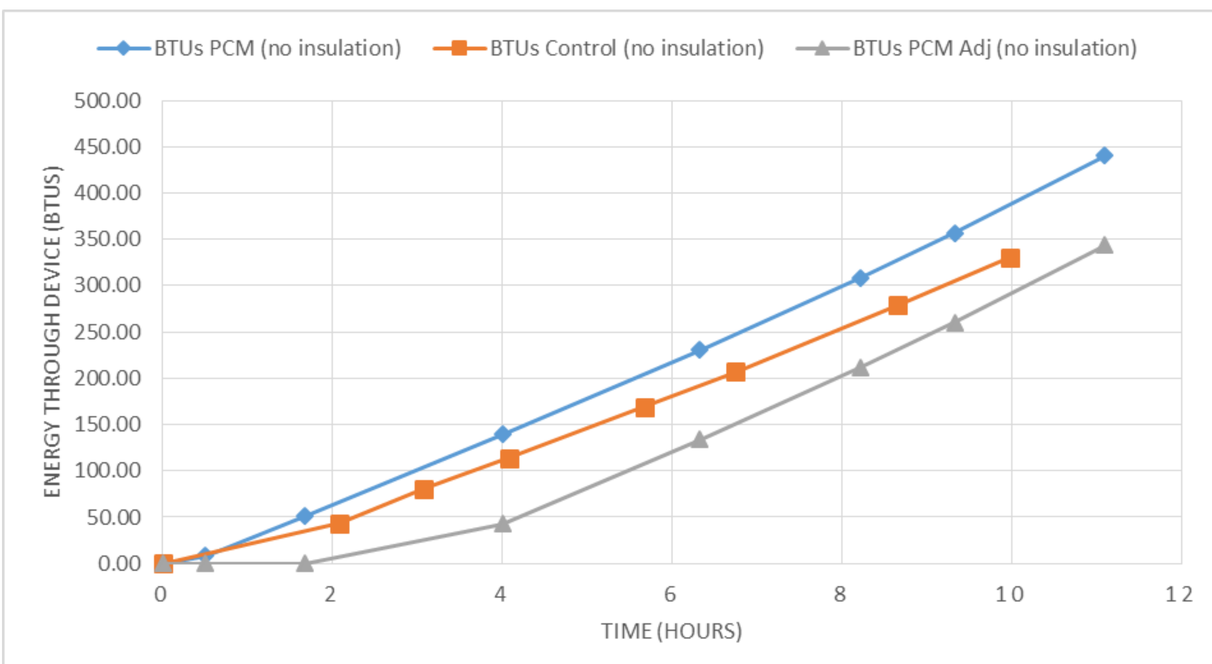

Figure 10: BTUs v. Time without Insulation

Chapter 4: Discussion

Using the manufacture of the PCM's website, it was determined that the M27 notation on the PCM signified the energy that the PCM could absorb. In this case, the M27 PCM could absorb 27 Btu/ft^2 before no longer being able to absorb any additional heat [19].

Once the PCM loses its ability to retain additional heat, it will begin to act like any other component in a wall. Since PCM has such a low thermal resistance, the majority of its benefit lies in its ability to absorb this heat [13].

As can be observed in the analysis section, the PCM's energy storage exceeded 27 Btu/ft^2 during the recorded intervals, with and without the insulation (Figure 8). This observation would suggest that the PCM did fully liquefy during the experiment, assuming all heat into the PCM was stored and none was lost to the air conditioned room.

This being said, when the PCM completely liquefied it was expected to see an increase in temperature thereafter with a larger slope than previously observed. Once the data was collected from all five phases, no distinctive change in slope was observed in the temperature v. time plots.

Why there was no distinct increase in temperature as a result of this experiment can be attributed to several causes, all of which will be discussed in more detail:

- The temperature in the room was maintained between 66 F and 69 F during all points during this experiment.
- Temperatures were directly recorded only on the inside and outside of wall section.

The room the experiment was conducted in was maintained between 66 F and 69 F which is considered to be lower than the average household would set their thermostats, particularly in the summer. In fact, 66 F is upwards of 10 degrees cooler than an average household would set their thermostats to.

Since the areas where the temperatures were being recorded were between 0.5 and 4 in. away from the phase change layer within the wall, there was an opportunity for the increase in temperature in the PCM post phase change to be unobservable. This could be due to leakage in the walls or due to the low temperatures in the room cooling the outside of the device.

The ideal situation described in the analysis section describes the assumption that no energy stored within the PCM was lost to the air conditioned room. If this assumption is incorrect and there was energy leaving the PCM layer at a rate that prevented it from reaching its thermal capacity, this would be a potential reason for not observing an increase of temperature in the outside wall.

A secondary means of determining the PCM temperature would be to incorporate one or two thermocouples into the wall, touching the inside and outside of the PCM. This would give an accurate depiction of the PCM temperature with respect to the overall temperature differences across the wall. This technique could also reduce error due to leakages and low temperatures in the room.

Though a phase change is unobservable, there is a difference between temperature between the control and the PCM configurations, both with and without insulation. This observation coincidences with the objective of the phase change materials, to lower heating and cooling costs for a given space. In this case, the average "internal" wall temperature was approximately 1.6 degrees Fahrenheit lower than the control, and approximately 4 degrees Fahrenheit lower for the experiment without the insulation as shown in Figure 5.

As shown in Figure 9 and 10, the total BTUs transferred through the wall was higher for experiments involving the PCM relative to the control, this is potentially due to an incorrect assumption that the thermal resistance of the PCM is negligible. If the thermal resistance of the PCM is calculated using the thermal conductivity referenced in Muruganantham's study of bio-pcm (0.2 W/m K), the BTUs through the system would be reduced below that of the control for the configurations with and without insulation [13].

To compensate for this result that seems to contradict the purpose of PCM, the assumption is made that the PCM absorbs all heat before reaching its advertised thermal capacity which generates the adjusted total BTUs through the system as discussed in the analysis section (Tables 8 and 9). With this new total BTUs calculation, the PCM appears to perform better than the control by preventing more heat from entering the air conditioned room for both the insulation configurations (Figures 9 and 10).

Several additional reasons why the results produced are contrary to what was expected could be due to uncompensated for losses as well as uncompensated for storages of heat in the mathematics. As an example, consider the gypsum board. Gypsum has a specific heat of 0.21 Btu/lbm F and a density of 40 lbs/ft^3. Therefore, the heat required to raise the gypsum board used in this experiment by one degree F is approximately 0.62 BTUs (or 8.4 Btu / ft^3 F).

Since the thermal capacity of the gypsum board was not considered, this could have also affected the calculations.

For the remainder of this discussion, the situations involving no insulation will be disregarded as few homes are designed without this feature.

If the BTUs through the wall and the PCM are averaged over the length of the experiments a difference in BTUs per hour can be calculated, this will be referred to as the BTU per hour savings. When converted to kilowatts and multiplied by 12 to approximate the number of daylight hours, a savings and kilowatt-hours can be calculated (Table 15).

Table 12: BTU Comparison PCM v. Control

Description	PCM	Control
Total Device Btu	35.633	78.564
Total Time (hours)	10.850	9.990
Average Device Btu/hr	3.284	7.864
Comparision	With Insulation	
Btu / hr Savings	4.580	
Percent Savings	58%	
Savings (kw)	0.001	
Savings per Day (kwh)	0.016	

Theoretical Case Study

Consider a home with 1600 sq. ft. This home has equal length walls to form a square, each wall being approximately 40 feet in length. This small home has ceiling heights of 8 feet giving it a wall area of 320 sq. feet per side for a total of 1280 sq. feet, approximately 720 times larger than the size of the 16 by 16 inch sample tested in this experiment.

If the previously calculated kilowatt-hour savings (Table 13) is multiplied by this factor, an estimated savings can be calculated for a 1280 sq. foot area. Assuming a coefficient of performance for an air conditioner or 3.0, the energy savings in kilowatt hours can be calculated for the home. Using an estimated $0.12 cents per kwh, a savings per day can be calculated along with a savings per month. These numbers are based solely off the temperatures observed in the experiment and are not necessarily realistic.

Table 13: Considering a 1600 sq. ft house

For a 1600 sq ft house in the Summer			
Description	Ideal	Realistic	Notes
Total External Wall Area (sq ft)	1280.00	960.00	Only about 75% PCM coverage
Multiplier	720.32	324.14	Whole house not exposed to direct sunlight all the time
Coefficient of Performance (COP)	3.00		
Energy Savings (kwh)	3.87	1.74	
Cost per kwh	0.12	0.12	
Energy Savings (per day)	$ 0.46	$ 0.21	
Energy Savings (per month)	$ 13.92	$ 6.27	

This being said, a realistic calculation also can be made to take into account the insufficiencies in the data. Several accommodations were made to create a more conservative savings estimate:

- The original 1280 was reduced to 896 assuming that only 75% of the available space could utilize the PCM material.
- The multiplier was reduced by 40% (324.14) to account for the movement of the sun. Since the experiment was for an area under direct sunlight this would not be a realistic assumption to make for the entire home.

In order to justify the purchase and installation of a PCM material there must be a reasonable payback period. Referencing Suns economic analysis of PCM, it costs approximately $2 per m^2 of PCM [17]. Using this cost, a total cost of material was estimated for the home. A savings per year was calculated for a given year by multiplying the savings per month by 12.

This being said, a realistic calculation also can be made to take into account the insufficiencies in the data. Several accommodations were made to create a more conservative savings estimate:

- Since installation isn't free, 25% was added on top of the entire cost of materials.
- Since the gypsum walls were increasing to 113 F at some points it can be said that the experiment replicated the temperatures of a hot and dry summer day. To account for the cooler months of the year the overall savings was reduced by 25% ($56.39) in order to come to an additionally conservative conclusion.

Once these accommodations were made the cost of materials and labor were divided by the savings per year to come up with a payback period in years of approximately 4 years conservatively. Though significant uncertainty exists in this calculation, a home owner with a 15 to 30 year mortgage has an opportunity to save money from at most 4 years out.

Table 14: Payback Period of Theoretical Case Study

Description	Ideal	Realistic	Notes
Cost of PCM ($/m^2)	$ 2.00	$ 2.00	
Cost of PCM ($/ft^2)	$ 0.19	$ 0.19	
Total Cost PCM	$ 237.83	$ 222.97	
Energy Savings per year	$ 167.08	$ 56.39	With changing climates, multiplied by 75% to be conservative
Payback Period (Years)	1.5	4.0	Rounded up to nearest tenth

Sources of Error

There are several sources of error in the experiment that must be accounted for before reviewing any conclusions:

- Gaps between the foam board and the wall used in the experiment which may have allowed heat to escape.
- The plastic bag covering the rear of the device was not secured completely to the device which allowed the warm air accumulating inside of the device an opportunity to escape.
- The lamp was not in the exact position for all phases of the experiment as it needed to be moved occasionally.
- The thermal images were not all taken at precisely the same location since all images were captured by hand.
- The insulation was not installed professionally and may not have been the proper resistance for the application.
- During phase 5 of the experiment, several students came and went in the room that the experiment was taking place and often were within 5 feet of the data logging device’s thermocouple which may have altered some of the data points.
- The thermal capacity for all materials in the experiment were not included in calculations.

Chapter 5: Conclusions

Based on the observations made and data collected the following conclusions can be made:

- Using Bio PCM in a wall under direct sunlight can reduce the internal wall’s surface temperature by approximately 2 F during the daylight hours.
- M27 Bio PCM has sufficient energy storage capacity to absorb heat from a source causing surface temperatures of approximately 105 F in a properly insulated wall to reduce the temperature of the internal wall for at least 7 hours.
- Bio PCM can be used to reduce the overall cooling cost for a home if it is installed properly in a warmer climate and has a payback period of at most 4.0 years assuming all heat entering the PCM is stored.

How the Experiment could be improved

If done over now that all of the data is within view, there would be several changes made to the experiment.

As mentioned, the proper insulation would have been researched and used in the wall of the device. This insulation would help prevent additional heat from escaping and potentially allow the heat to focus on the 16 inch by 16 inch space with the PCM.

The fraction of the 125 W heat lamps energy entering the 16 by 16 inch space would have been estimated to draw additional conclusions about the validity of the results produced by this experiment. These calculations were attempted during the analysis of this experiment; however, due to time constraints the results of these calculations were not verified and could not be included in this report.

Based on the Bio PCM website, there are certain PCM “blankets” that are suitable for different walls of the home [19]:

- South – M51
- West – M51
- East – M27
- North – M27 (or no PCM depending on the climate)

These recommendations are based on the position of the sun throughout the day. If the limit of the experiment was simply one device with a 16 by 16 envelope, the M51 material would have been tested in additional phases of the experiment.

To build on this idea, a means of orienting or positioning the lamp would have been devised to simulate the different wall sides of a home. This data would then be used to more accurately predict the savings from the Bio PCM material.

In order to make the experiment more realistic, a larger heat source could have been used to more accurately simulate the intense rays of the sun, this may have allowed the M27, or even the M51, to reach its heat flux capacity which would have allowed a change in slope of the temperature v. time graph to be potentially more observable.

Brick or siding could be used if a more intense heat source was to be added to the experiment, this would again increase the overall realism of the experiment.

From a timing perspective, ideally the experiment would be run 24 hours a day for multiple days with the lamp running only during daylight hours to give the PCM time to “recharge”.

Several thermocouples could have been used to monitor the device more continuously, especially if the idea of running the experiment at night was an option.

Several of the papers cited in the Background section referenced night purge as a means of allowing the space to utilize cool night air to assist in the “recharging” of the PCM. This process was in fact used during the experiment when the trash bag on the rear of the device was lifted to allow the space to return to room temperature. If monitoring was to occurring during the night, this would be an interested process to map with data. Additionally, the experiment could be run for multiple days with and without the night purge to see the differences in temperatures.

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Appendices

Appendix A

Organic PCM – Paraffin and non-paraffin

Advantages

- Available in large temperature range (from approximately 20 °C up to about 70 °C)
- Chemically inert
- Do not undergo phase segregation
- Thermally reliable in long run (freeze melt cycle)
- Have low vapour pressure in the melt form
- Reasonable latent heat of fusion (120 J/g up to 210 J/g)
- Paraffins have high specific heat than salt hydrates
- Non-corrosive, however, fatty acids are mildly corrosive
- Inexpensive, however, fatty acids are 2–2.5 times expensive than technical grade paraffin
- Compatible with construction materials
- Small volume change during phase transition
- Little or no supercooling during freezing
- Innocuous (Neither toxic nor irritant, however, non-paraffins show varying level of toxicity)
- Stable below 500 °C, however, non-paraffins show instability at high temperature
- Recyclable

Disadvantages

- Low thermal conductivity (around 0.2 W/m.K)
- Moderately flammable
- Non-compatible with plastic containers

Inorganic PCM – Salt hydrates

Advantages

- High volumetric latent heat storage (Almost double than that of organic materials)
- High latent heat of fusion
- High thermal conductivity (0.5 W/m.K)
- Cheaper and readily available
- Non-flammable
- Compatible with plastic containers
- Sharp phase change
- Low environmental impact
- Having recycling potential

Disadvantages

- Undergo supercooling during freezing
- Undergo phase segregation during transition
- Corrosive to most metals
- Irritant
- Have high vapor pressure (Induce water loss and cause progressive change in thermal behavior during thermal cycling process)
- May show long term degradation by oxidization, hydrolysis, thermal decomposition and other reactions
- Exhibit variable chemical stability
- High volume change

Eutectic

Advantages

- In general have sharp melting temperature
- High volumetric thermal storage density (slightly above organic PCM)

Disadvantages

- Limited test data available on their thermo-physical properties

Figure 11: Advantages and Disadvantages of PCM [10]

Appendix B: Tables

Table 15: PCM with Insulation Data

PCM with Insulation						
Time	Hours	Inside Temp (°F)	AC Temp (°F)	Inside Wall Temp (°F)	Inside Wall Temp Adj (°F)	Outside Wall Temp (°F)
9:13:00 AM	0	66.5	66.5	67.8	67.8	67.8
9:41:00 AM	0.46	87.3	66.5	91	88	69.3
10:13:00 AM	1	92.4	66.5	107	104	68.2
10:46:00 AM	1.55	93.2	66.5	110	107	69.1
11:22:00 AM	2.15	94.7	66	111	108	69.6
12:34:00 PM	3.35	95.3	66.5	114	111	69.3
1:31:00 PM	4.3	96.3	66	114	111	69.3
2:20:00 PM	5.11	94	66	112	109	69.6
3:40:00 PM	6.45	91	66	105	102	70
4:40:00 PM	7.45	94.6	66.5	113	110	70
6:50:00 PM	9.61	94.7	66	113	110	69.4
8:04:00 PM	10.85	95.2	66.5	112	109	69.8

Table 16: PCM without Insulation Data

PCM without Insulation								
Time	Hours	Inside Temp (°F)	AC Temp (°F)	Inside Wall Temp (°F)	Inside Wall Temp Adj (°F)	Outside Wall Temp (°F)	Data Logger (°F)	Error
7:30:00 AM	0	69	69	69	69	69	67.87	2%
8:00:00 AM	0.5	89.5	66.5	94.5	91.5	69.3	68.49	1%
9:10:00 AM	1.67	91.9	67	99	96	70.3	69.71	1%
11:30:00 AM	4	92.4	67	98.8	95.8	72.1	70.3	2%
1:50:00 PM	6.33	97	67	103	100	72.5	71.53	1%
3:43:00 PM	8.22	97.4	67.5	103	100	73.6	71.53	3%
4:50:00 PM	9.33	102	68	108	105	73.8	72.12	2%
6:36:00 PM	11.1	100	67.5	107	104	73.8	72.12	2%

Table 17: Control with Insulation Data

Control with Insulation					
Time	Hours	Inside Temp (^oF)	AC Temp (^oF)	Inside Wall Temp (^oF)	Outside Wall Temp (^oF)
9:08:00 AM	0	68.9	69	70.2	70
9:46:00 AM	0.64	93.6	66.5	104	69.3
11:00:00 AM	1.87	95.6	66.5	110	71.1
12:00:00 PM	2.87	93.8	66.5	108	70.9
1:48:00 PM	4.67	98.9	66.5	115	70.9
4:09:00 PM	7.02	93.7	66	109	71.6
6:13:00 PM	9.09	94.4	66	110	71.4
7:07:00 PM	9.99	95.1	66.5	110	71.8

Table 18: Control without Insulation Data

Control without Insulation					
Time	Hours	Inside Temp (^oF)	AC Temp (^oF)	Inside Wall Temp (^oF)	Outside Wall Temp (^oF)
7:45 AM	0	72.8	69.5	72.1	70.7
9:50 AM	2.08	102	67.5	105	75.9
10:50 AM	3.08	98.6	67.5	101	76.1
11:50 AM	4.08	98.2	68	101	76.3
1:25 PM	5.67	99.4	68	104	77.4
2:30 PM	6.75	97.3	68	103	77.2
4:24 PM	8.65	104	68	107	77.5
5:44 PM	9.98	102	68	106	78.1

Appendix C: Materials and Assembly

Figure 12: Brooder Lamp with Grow Bulb

Figure 13: 2x4 Stud Cut to lengths

Figure 14: Insulation

Figure 16: Reflective Tape

Figure 18: Aluminum Faced Foam

Figure 19: Bio PCM Phase Change Material

Figure 20: Assembled H-Frame

Figure 21: Assembled H-Frame with Center Insulation

Figure 22: PCM Attached to H-Frame

Figure 23: Side Insulation

Figure 24: Completed Assembly View 1

Figure 25: Completed Assembly View 2

Figure 26: Attached Trash Bag

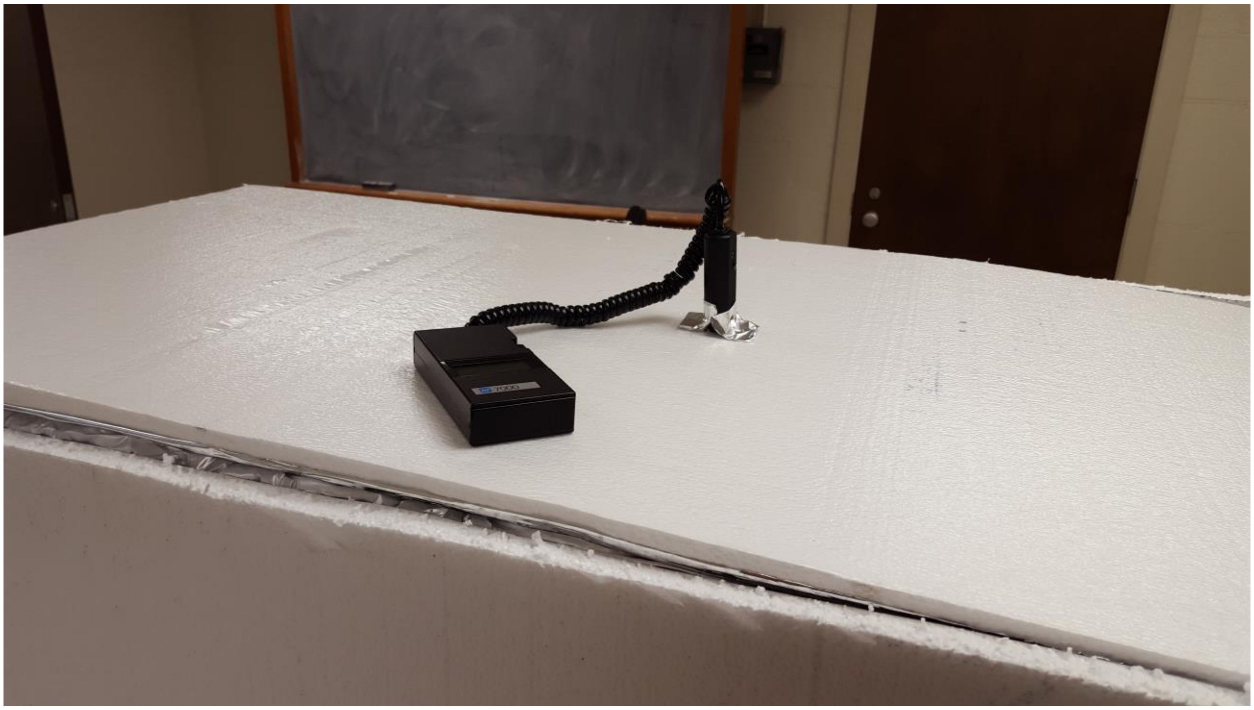

Figure 27: Bored hole with pyrometer

Figure 29: End of Device without PCM

Figure 30: Device with Temperature Humidity Meter

Figure 31: Temperature Humidity Meter

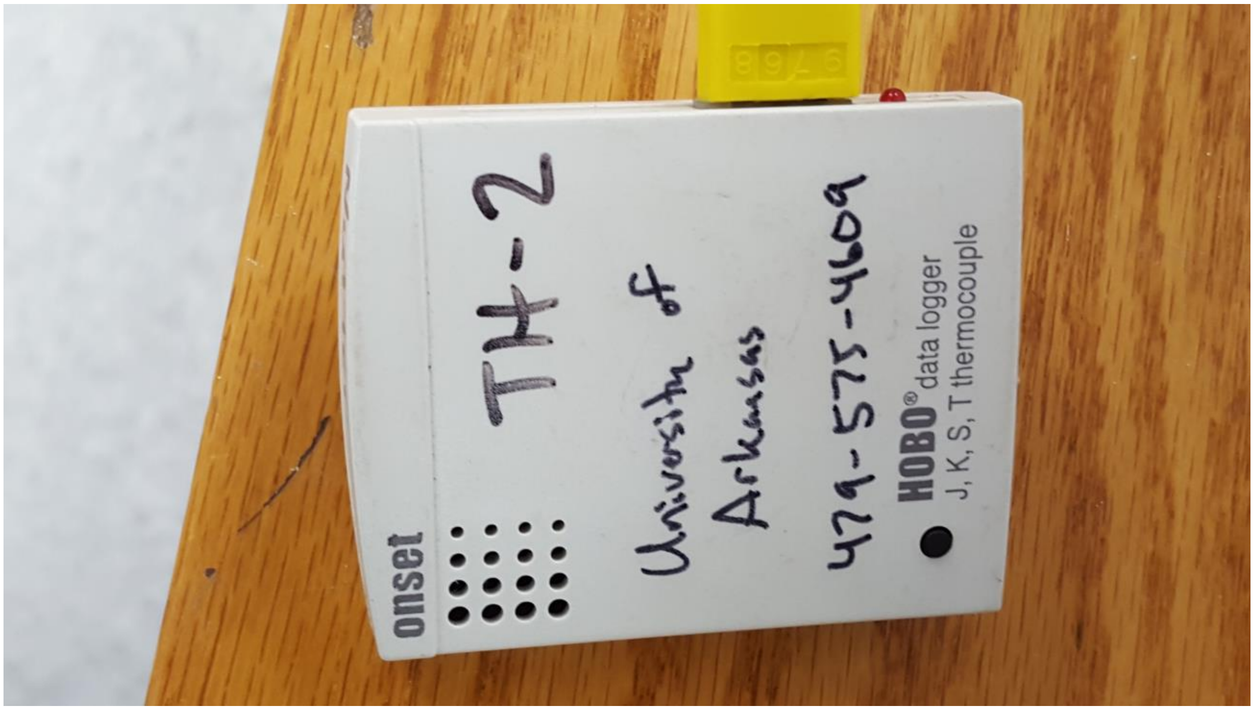

Figure 32: Datalogger

Figure 33: Thermocouple Attached to Device

Figure 34: Infrared Camera

Appendix D: Raw Data

Table 19: Data Logger Raw Data Sample

Plot Title: Temperature TH-2		
#	Date Time, GMT-05:00	K-Type, °F (LGR S/N: 884519, SEN S/N: 884519)
1	4/25/2016 7:41	73.35
2	4/25/2016 7:42	67.87
3	4/25/2016 7:43	71.53
4	4/25/2016 7:44	68.49
5	4/25/2016 7:45	67.87
6	4/25/2016 7:45	
7	4/25/2016 7:46	67.87
8	4/25/2016 7:47	67.28
9	4/25/2016 7:48	67.28
10	4/25/2016 7:49	67.28
11	4/25/2016 7:50	67.28
12	4/25/2016 7:51	67.28
13	4/25/2016 7:52	67.28
14	4/25/2016 7:53	67.28
15	4/25/2016 7:54	67.28
16	4/25/2016 7:55	67.28
17	4/25/2016 7:56	67.28
18	4/25/2016 7:57	67.28
19	4/25/2016 7:58	67.28
20	4/25/2016 7:59	67.28
21	4/25/2016 8:00	67.28
22	4/25/2016 8:01	67.87
23	4/25/2016 8:02	67.28
24	4/25/2016 8:03	67.87
25	4/25/2016 8:04	67.87
26	4/25/2016 8:05	67.87
27	4/25/2016 8:06	67.87
28	4/25/2016 8:07	67.87
29	4/25/2016 8:08	67.87

Appendix E: Thermal Images

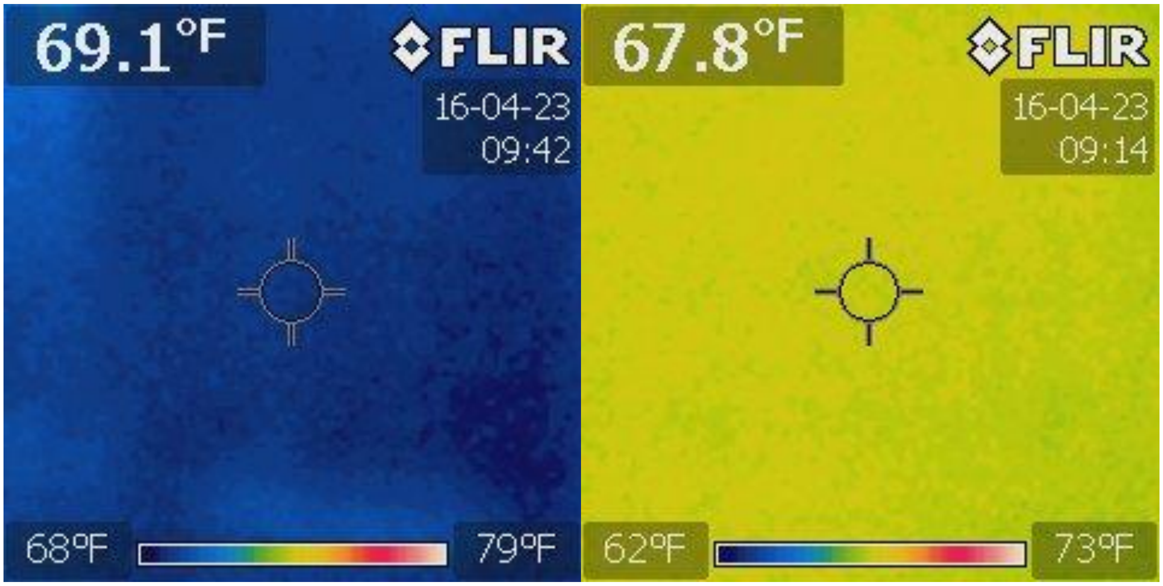

Figure 35: Phase 2 Start of Day (outside on right, inside on left) NOTE: timestamps are off due to malfunction

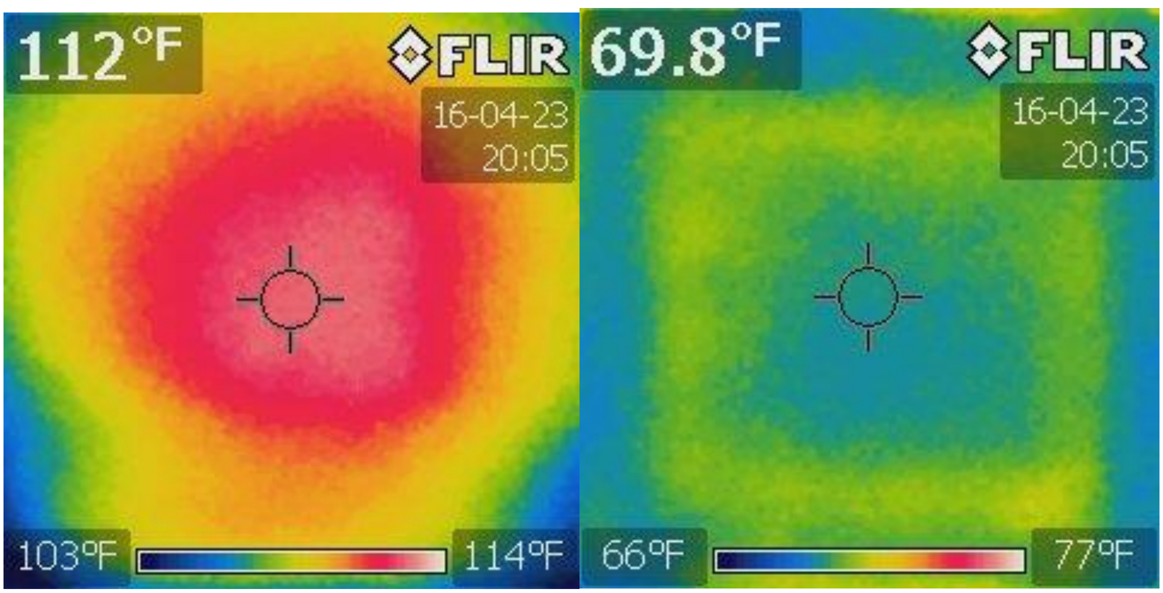

Figure 36: Phase 2 End of Day (outside on right, inside on left)

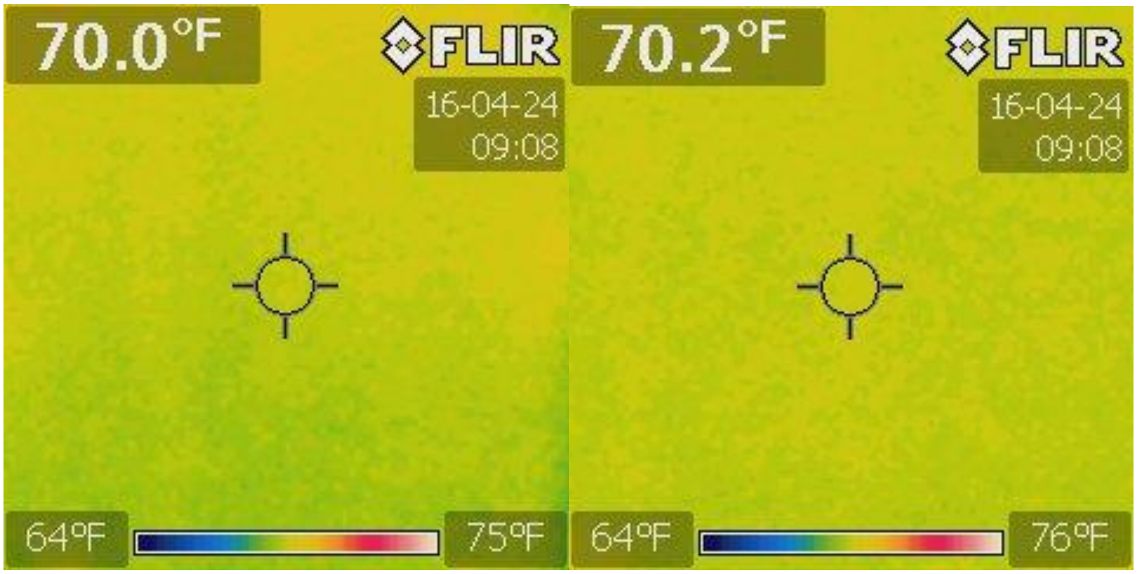

Figure 37: Phase 3 Start of Day (outside on right, inside on left)

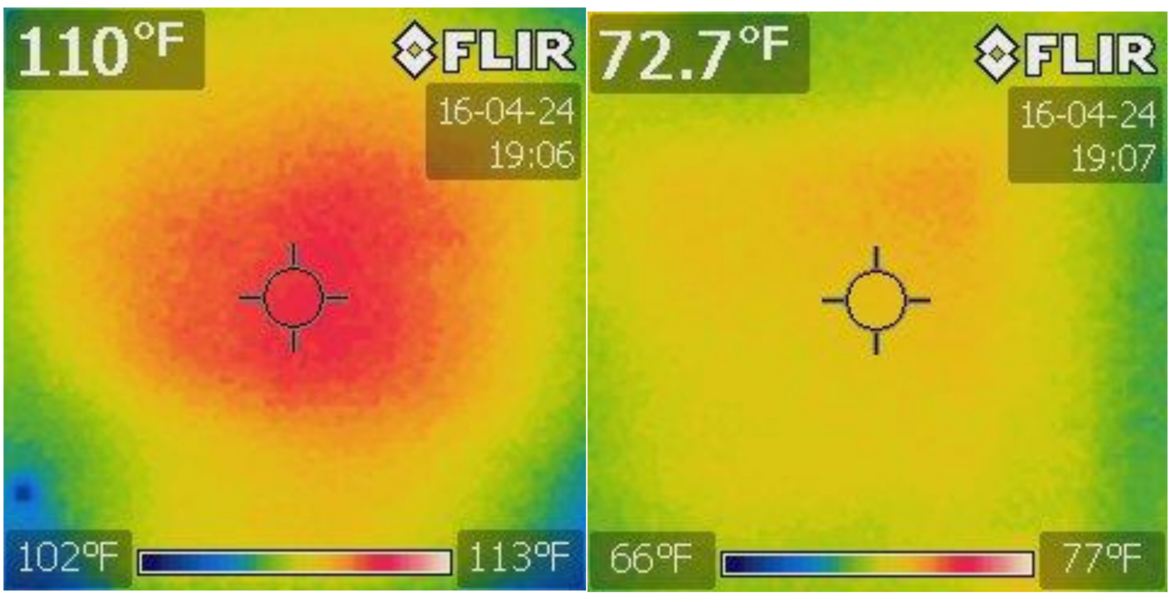

Figure 38: Phase 3 End of Day (outside on right, inside on left)

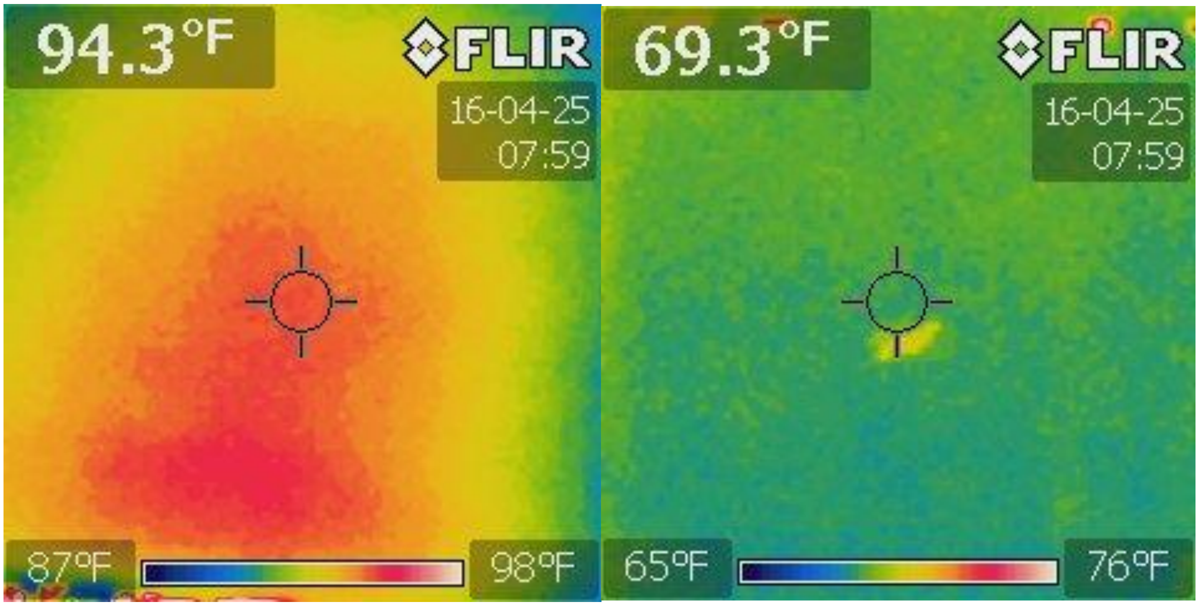

Figure 39: Phase 4 Start of Day (outside on right, inside on left)

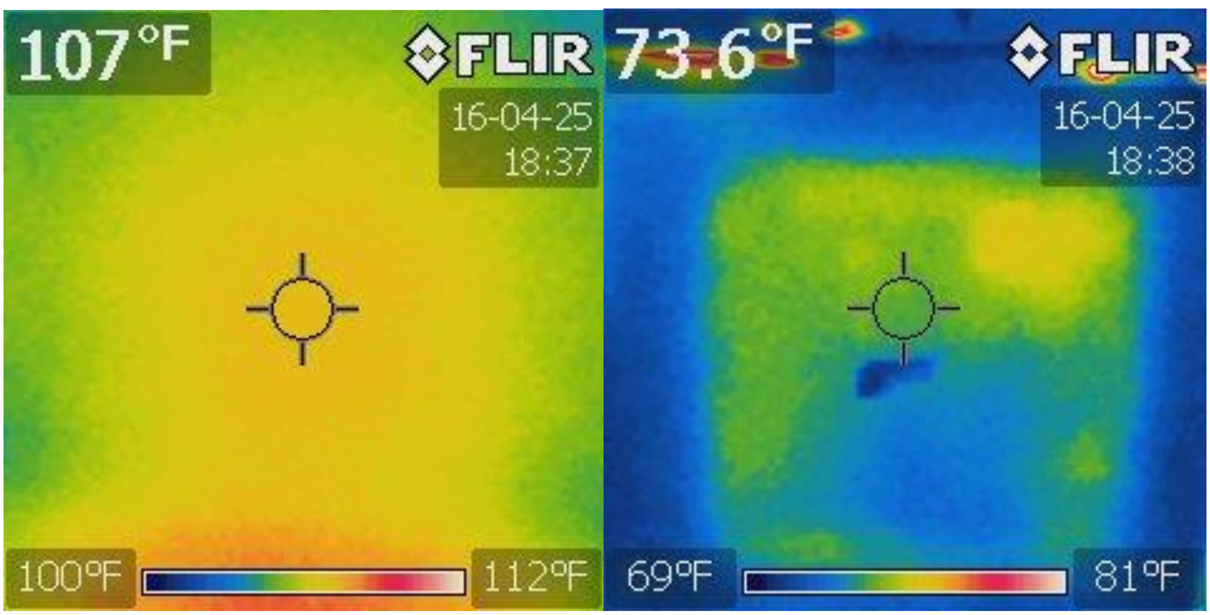

Figure 40: Phase 4 End of Day (outside on right, inside on left)

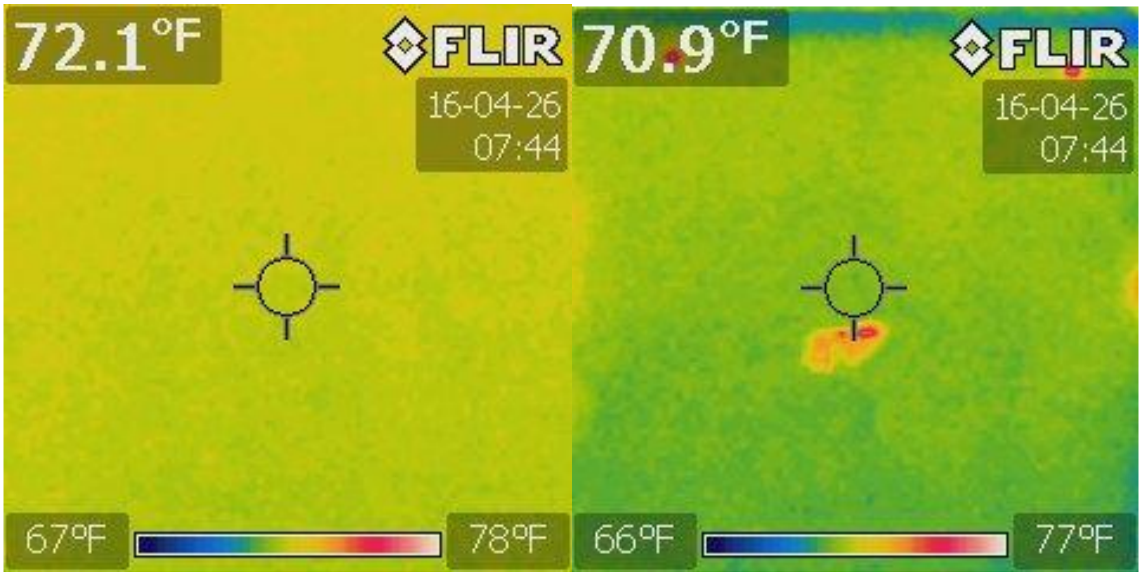

Figure 41: Phase 5 Start of Day (outside on right, inside on left)

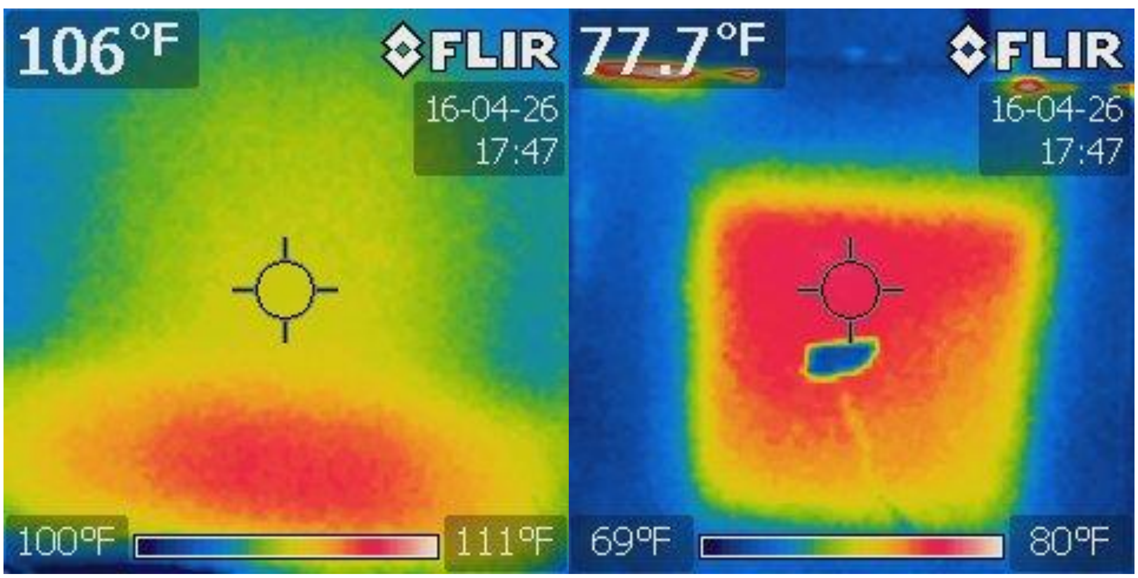

Figure 42: Phase 5 End of Day (outside on right, inside on left)

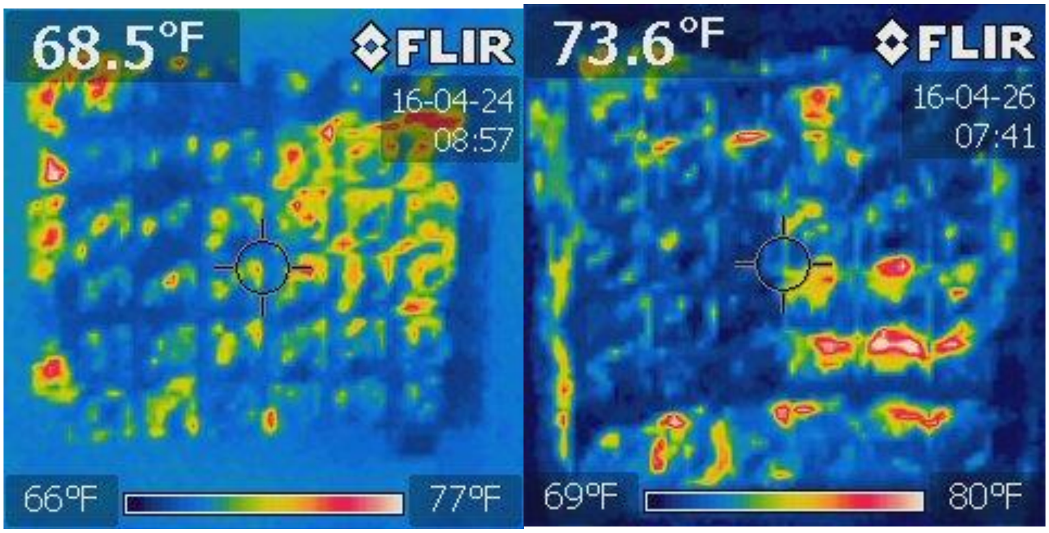

Figure 43: PCM Start of Day after Phase 2 (left) and Phase 4 (right)

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